

A Treatise on the Thresholds of Interoctave Frequencies: 1500, 3000, and 6000 Hz

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Abstract

Background: For the past 50+ years, audiologists have been taught to measure the pure-tone thresholds at the interoctave frequencies when the thresholds at adjacent octave frequencies differ by 20 dB or more. Although this so-called 20 dB rule is logical when enhanced audiometric resolution is required, the origin of the rule is elusive, and a thorough literature search failed to find supporting scientific data.

Purpose: This study purposed to examine whether a 20 dB difference between thresholds at adjacent octave frequencies is the critical value for whether the threshold of the interoctave frequency should be measured. Along this same line of questioning is whether interoctave thresholds can be predicted from the thresholds of the adjacent or bounding octave frequencies instead of measured, thereby saving valuable time.

Research Design: Retrospective, descriptive, correlational, and cross-sectional.

Study Sample: Audiograms from over a million veterans provided the data, which were archived at the Department of Veterans Affairs, Denver Acquisition and Logistics Center.

Data Collection and Analysis: Data from the left and right ears were independently evaluated. For each ear three interoctave frequencies (1500, 3000, and 6000 Hz) were studied. For inclusion, thresholds at the interoctave frequency and the two bounding octave frequencies had to be measurable, which produced unequal numbers of participants in each of the six conditions (2 ears by 3 interoctave frequencies). Age tags were maintained with each of the six conditions.

Results: Three areas of analyses were considered. First, relations among the octave-frequency thresholds were examined. About 62% of the 1000–2000 Hz threshold differences were ≥ 20 dB, whereas about 74% of the 4000–8000 Hz threshold differences were < 20 dB. About half of the threshold differences between 2000 and 4000 Hz were < 20 dB and half were > 20 dB. There was an inverse relation between frequency and the percent of negative slopes between octave-frequency thresholds, ranging from 89% at 1500 Hz to 54% at 6000 Hz. The majority of octave-frequency pairs demonstrated poorer thresholds for the higher frequency of the pair. Second, interoctave frequency thresholds were evaluated using the median metric. As the interoctave frequency increased from 1500 to 6000 Hz, the percent of thresholds at the interoctave frequencies that were not equal to the median threshold increased from $\sim 9.5\%$ (1500 Hz) to 15.6% (3000 Hz) to 28.2% (6000 Hz). Bivariate plots of the interoctave thresholds and the mean octave-frequency thresholds produced 0.85–0.91 R^2 values and 0.79–0.92 dB/dB slopes. Third, the predictability of the interoctave thresholds from the mean thresholds of the bounding octave frequencies was evaluated. As expected, as the disparity between octave-frequency thresholds increased, the predictability of the interoctave threshold decreased; for example, using a ± 5 dB criterion at 1500 Hz, 53% of the thresholds were ± 5 dB when the octave thresholds differed by ≥ 20 dB, whereas 77% were ± 5 dB when the octave thresholds differed by < 20 dB.

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Conclusions: The current findings support the 20 dB rule for testing interoctave frequency thresholds and suggest the rule could be increased to 25 dB or more with little adverse effect.

Key Words: Audiometry, auditory perception, auditory threshold, hearing loss, inter-octave frequency threshold, pure-tone audiometry, pure-tone thresholds

Abbreviations: ANSI = American National Standards Institute; ASHA = American Speech-Language-Hearing Association; cps = cycles per second; DALC = Denver Acquisition and Logistics Center; d.v. = double vibrations (Hertz); *n* = number; VA = Department of Veterans Affairs

Since the senior author entered audiology in the early 1960s, one of the “rules” for pure-tone testing has been to obtain thresholds at the interoctave frequencies (typically, 1500, 3000, and 6000 Hz) when the thresholds at the two adjacent octave frequencies differ by 20 dB or more.¹ This so-called 20 dB rule (i.e., ≥ 20 dB) is tempered somewhat in the current American National Standards Institute (ANSI) standard for pure-tone audiometry, which states, “Threshold measurements shall be made at octave intervals from 250–8000 Hz and at intermediate frequencies as required to satisfy the purposes for which the procedure is being used” (2004, p. 6). The American Speech-Language-Hearing Association (ASHA, 2005) guideline for pure-tone audiometry is more specific and for the first time indicates that, in addition to the octave frequencies suggested by ANSI, thresholds at 3000 and 6000 Hz should be established. The reason for the inclusion of these two interoctave frequencies in the ASHA guideline was to provide “a more complete profile of the participant’s hearing status” (2005). For the lower frequencies (500–2000 Hz), the ASHA guideline evokes the above mentioned 20 dB rule. Although the 20 dB rule may be logical, the rule must be placed in the category of audiology folklore until a scientific basis is provided. The purpose of this report is to examine the relations among octave frequency thresholds and their interoctave frequency thresholds in an effort to provide data supporting or refuting the 20 dB rule. As the aforementioned rule involves the audiogram, three areas of the audiometer/audiogram literature were searched in an effort to identify the source of the 20 dB rule, including articles, standards, and textbooks.

In the latter part of the 19th century, electricity was used increasingly to power the gamut of scientific devices including tuning forks and eventually the vacuum tube that led to the audiometer as we know it today. For example, Richardson, who is often credited for coining the term *audiometer*, stated, “I hope I have related enough to show that the world of science in general, and the world of medicine in particular, is under a deep debt of gratitude to Professor Hughes for his simple and beautiful instrument, which I have christened the audiometer, or less correctly but more euphoniously, the audiometer” (1879, p. 70). The Hughes (1879) instrument involved a clock as the sound source, a microphone

transducer, induction coils and a sonometer for amplitude control, and a telephone to transduce the electrical signal to an acoustic signal, all powered by a battery. From this early benchmark of auditory measurement, the refinements made to the audiometer and the evolution of the audiogram paralleled one another. (Note: a recent article by Jerger (2013) describes the evolution of the audiogram and why it is “upside-down.”)

In the 1800s, the tuning fork, which was invented in England by John Shore in 1711 (Bickerton and Barr, 1987), was widely used to test hearing in a variety of paradigms including those devised in Germany by Weber, Rinne, and Schwabach. In 1881, Hartmann used six tuning forks to test hearing (128, 256, 512, 1024, 2048, and 3072 Hz, which corresponded to c to c4 and g4), the results of which he graphed on an early form of the audiogram (Hartmann, 1887, p. 33). Even today, 130 yr later, the “Hartmann tuning fork set” (128 to 2048 Hz) is considered essential in otologic practice.

A 1913 paper by Gradenigo reflects the transition from tuning forks to electrically generated signals (acoumeter) that was taking place during that decade. Gradenigo also was concerned with the calibration of speech and tonal signals used to measure the “hearing power” and how the hearing power of individuals could be plotted in a graphic format similar to graphs used in temperature charts. A collaborative effort by Dean and Bunch (1919) produced an audiometer that measured, “the tonal range from 30 double vibrations to 10,000 double vibrations” (p. 454). They plotted their data on a grid-free, hand-drawn graph with “Pitch” on the abscissa ranging from 200 to 3200 d.v. and “Intensity” on the ordinate ranging in unspecified units from 1 to 7 (probably sensation units). Other custom audiometers were developed by several laboratories, but none were commercialized (e.g., Minton and Wilson [1921]; Guttman [1921]). Fowler and Wegel (1922) described the parameters of an audiogram in relation to the newly developed electric audiometer. In discussing the nomenclature of the audiogram, which by that time had established the abscissa for signal frequency and the ordinate for signal amplitude, Fowler and Wegel (1922) indicated that each axis of the audiogram could be plotted using one of two conventions. Frequency on the abscissa could be plotted in either equal arithmetic intervals or equal logarithmic intervals, the latter exemplifying a musical

scale.² They reasoned that, "Since the sensation of pitch change corresponds more nearly to musical intervals than to equal frequency intervals, the musical scale is the more logical to use in an audiogram" (1922, p. 99). Thus in the 1920s, the frequencies used to test auditory sensitivity were powers of two (e.g., 64, 128, 256 Hz, etc.), which followed the frequency standards established for tuning forks in the 1800s. This convention of frequency designation continued through the late 1940s evidenced by the Thompson article reporting the recommendations by the Committee on the Conservation of Hearing of the American Academy of Ophthalmology and Otolaryngology in which she listed the test frequencies using the powers of two convention, but in a footnote she noted, "Round figures 120, 250, . . . and 8000 may be substituted if this change is made in accepted commercial audiometers" (1947, p. 363). This rounded test frequency nomenclature subsequently was incorporated into the 1951 audiometry standard developed by the American Standards Association that minimally required octave frequencies from 125 to 8000 cycles per second (cps). Although the ordinal values of the audiogram are the focus of this article, there are some subtle features of the audiogram abscissa that impact the relations among the ordinal values. The interoctave frequency is the arithmetic mean of the two bounding octave frequencies; for example, 1500 Hz is the mean of 1000 and 2000 Hz. As frequency on the audiogram is plotted in \log_{10} units, however, the half octave frequency would be the antilog of the mean of the logs of the two frequencies. In the example above, the \log_{10} of 1000 is 3.0 and the \log_{10} of 2000 is 3.301, the mean of which is 3.1505; the antilog of 3.1505 is 1414. Thus, the difference between the two mean calculations (1500 – 1414) is 86 Hz. As frequency increases, the differences between the arithmetic and logarithmic means increase such that at 3000 Hz the difference is 172 Hz (3000 – 2828) and at 6000 Hz the difference is 343 Hz (6000 – 5657). As detailed in Appendix A, the midpoints between the thresholds of two octave frequencies also are different for arithmetic and logarithmic calculations.

In the 1920s, quantification of the signal amplitude (ordinate on the audiogram) was more involved, especially as the decibel unit was at that time several years in the future. Fowler and Wegel (1922) acknowledged that the signal amplitude could be expressed in either pressure or energy terms, but in absolute terms those units (e.g., dynes) were exceedingly large requiring a logarithmic scale, for example, root mean square (rms) pressure in dynes per square cm (d/cm^2 ; Fletcher and Wegel, 1922; Wegel, 1922). Until the decibel was formalized and so named in 1928 (Hartley, 1928; Martin, 1929), the ordinal values of the audiogram typically were expressed either in logarithmic sensation/loudness units or in "percent of normal hearing," which Fowler and Wegel used with the 13 case studies they reported.

Although the audiogram was evolving through the first part of the 20th century, if there were a formalization of the 20 dB rule, then it was yet to come as the decibel was only defined in the latter part of this period.

Guttman and Ham (1930), in a paper discussing masking effects, used *decibels* to describe the signal amplitude and noted the abbreviation *db*. During the 1930s, the decibel was becoming commonplace as the units on the ordinate of various graphs depicting thresholds for pure tones (Fletcher, 1934). Typical is the classic minimum audible field and minimum audible pressure article by Sivian and White (1933) in which they expressed pure-tone thresholds in decibels with respect to a reference pressure. By the 1940s, the ordinal values of the audiogram took the form that we have today exemplified by the audiometric data developed at the 1939 World's Fairs in New York and San Francisco (Steinberg et al, 1940). In Steinberg et al, "Hearing acuity is expressed as a hearing loss in the usual way, i.e., the departure in db of a given test result from the reference level" (1940, p. 292). The reference level was the average thresholds for the 7495 participants in the 20–29 yr group. Interestingly, the World's Fairs data were obtained at 440 "cycles" and four multiples thereof; 440 Hz was the international/concert pitch for A above middle C. Hughson and Thompson (1942) also reported audiograms with thresholds at the octave frequencies in "Hearing Loss—Decibels" re "an established normal level" (p. 526) ranging from –10 (top) to 90 (bottom) with grid lines every 10 dB. During the 1930s and 1940s the audiogram evolved into its present form with octave frequencies on the abscissa, decibels hearing loss on the ordinate, and horizontal grid lines in 10 dB intervals. Mention of the 20 dB rule could not be found during this time period.

In 1939, the Council on Physical Therapy, which was organized under the American Medical Association, developed requirements for audiometers that included the octave frequencies between 128 and 8192 cycles per second. In the same document the recently unveiled decibel (Hartley, 1928; Martin, 1929) was recommended as the unit of measure for the "loudness" or amplitude of the tones with adjustments in steps of 5 dB. The report defined "the normal threshold of audibility as the modal value of the thresholds of audibility of a large number of normal ears of persons in the age group from 18 to 30 years" (p. 732). Also, the report suggested an aspect ratio of 20 dB per octave for the audiogram, but no mention was made of interoctave frequencies. Twelve years later, Fowler and Lüscher (1950), in a standardization subcommittee report, recommended, among other things, that reference levels be designated for audiometers and audiograms. As indicated above, (1) both the 1978 (p. 3) and 2004 (p. 6) versions of the American National Standard *Methods for Manual Pure-Tone Threshold Audiometry* (ANSI S3.21) indicated that thresholds at the intermediate (interoctave) frequencies were not

mandatory but, rather, should be made as required for the purpose under study, and (2) the 2005 ASHA pure-tone guidelines now recommend routinely testing 3000 and 6000 Hz to provide “a more complete profile” of the pure-tone threshold configuration. The ASHA guideline recommended the 20 dB rule be used in the octave intervals below 2000 Hz, but no data-based rationale was offered to substantiate this recommendation.

Over the years, most audiology textbooks make reference to the interoctave frequency thresholds but without any supporting documentation. In his classic textbook, *Clinical Audiology*, Bunch (1943) points out the importance of having “semi-octave tones” available on audiometers, which is an opinion that contrasted with an earlier statement by Fowler and Wegel that “half and one third octave points” were needless “for a better determination of the graph” (1922, p. 118). It should be pointed out that Bunch (1939) had an abiding interest in “traumatic deafness,” the audiometric completeness of which required examination with the interoctave frequencies, especially above 1000 Hz. According to Carhart, Bunch used the “gargantuan” Western Electric 1-A audiometer (of which less than a dozen were made) that had “half octave intervals from 32 through 16,394 Hz” (1970, p. 7). Bunch never specified a rule for testing the inter-octave frequencies; he just always tested them. Stevens and Davis, in their classic book, stated that, “The test tones usually have frequencies spaced an octave apart throughout the audible range, and the ‘normal’ intensity at each frequency is determined from measurements on a large group of young people” (1938, p. 60). Until recently, the thresholds at the interoctave frequencies were ancillary at best, exemplified by Newby in 1958. In his chapter on pure-tone audiometry, Newby stated, “If the loss pattern at the octave intervals is uneven, it may be desirable to obtain thresholds at the half-octave intervals: 750, 1500, 3000, 6000, and 12,000 cps” (1958, p. 77). Newby made no mention of the 20 dB difference rule; in fact, some of his example audiograms (e.g., fig. 5.4, p. 97) show octave threshold differences >20 dB with no measurement at the interoctave frequency. In the first edition of the *Handbook of Clinical Audiology* (Katz, 1972), the pure-tone threshold chapter indicated that “if the thresholds show significant rising or dropping between octaves, thresholds for 125 Hz and for the half octaves 750, 1500, 3000 and 6000 Hz may be explored to get a more complete assessment of the overall hearing configuration” (Green, 1972, p. 77). This line of thinking was continued in subsequent editions of the *Handbook of Clinical Audiology* (1) by Yantis, who stated, “Abrupt changes (20 dB) in threshold sensitivity occurring between standard test frequencies should be explored with half-octave signals” (1985, p. 159; 1994, p. 101), and (2) most recently by Schlauch and Nelson, “Intra-octave thresholds between 500 Hz and 2000 Hz should

be measured when thresholds differ by 20 dB or more between two adjacent octaves” (2009, p. 38). In all likelihood, if data were available to support the 20 dB rule, then the above texts would have included mention of such data.

The purpose of this project was to examine the relations among the thresholds of the adjacent octave frequencies and the threshold of the interoctave frequency using audiograms from over a million veterans collected throughout the Department of Veterans Affairs (VA) facilities that were archived in a national database that was developed and continues to be maintained by the Denver Acquisition and Logistics Center (DALC). In a previous article, these data were evaluated with respect to the high-frequency audiometric notches that are often observed in audiograms (Wilson and McArdle, 2013). The DALC database used was populated with audiometric data from VA facilities across the nation between 2002 and 2010. The database was restricted to one entry per participant. VA audiologists utilize the QUASAR (Quality: Audiology and Speech Analysis and Reporting) Audiogram Module, which is a Windows-based graphical user interface (GUI), developed to simplify and enhance the entry, display, and use of information obtained during an audiometric exam of a patient. The audiometric data such as pure-tone, air- and bone-conduction thresholds, aural acoustic immittance results, and speech recognition performance are entered and retrieved through the Computerized Patient Record System (CPRS) Tools menu that is the user interface of the VA electronic medical record. The audiometric data reside on two systems: the local facility VistA system (electronic medical record) and the DALC system.

METHODS

The DALC database that was obtained contained left ear and right ear audiograms from 1,000,001 veterans (2 million single-ear audiograms). The left-ear and right-ear audiograms for each participant were considered independently; that is, the audiograms for the two ears were not tied to one another. The inclusion criterion for this study was simple, thresholds had to be present at the interoctave frequency and the boundary octave frequencies of interest, of which there were the following three: (1) 1000, 1500, and 2000 Hz; (2) 2000, 3000, and 4000 Hz; and (3) 4000, 6000, and 8000 Hz. Each of these three data sets was independent. The data from the original database were “cleaned,” which mainly involved three issues. First, for inclusion only ages 20–90 were used. Because of privacy sensitivity issues, participants ≥90 yr were all considered to be 90 yr of age. Obvious data entry errors, for example, 1 yr of age, were eliminated. Second, data sets with threshold values that were not a multiple of 5 were discarded. There were two reasons for these “non-5 dB” thresholds.

A few sites entered thresholds in 1 or 2 dB steps, which produced some non-5 dB thresholds. Also, there were obvious data entry errors, for example, a 10 being entered instead of a 110. More often than not, it was difficult to determine which errors were data-entry errors and which were non-5 dB thresholds. Because the differentiation could not be made, these two categories of data sets were deleted. The deletions ranged from 208 participants for the 1500 Hz, left ear to 544 participants for the 3000 Hz, right ear. For each of the six data sets, less than 0.065% of the participants were eliminated from the analyses. The mean age of the group was 65.9 yr (SD = 15.9 yr).

RESULTS AND DISCUSSION

The impetus of this retrospective analysis was to examine whether a 20 dB difference between thresholds at adjacent octave frequencies is the critical value for whether a clinical audiologist should measure thresholds of an interoctave frequency. As was indicated in the introduction, this 20 dB difference is legendary, although the evidence base from which the 20 dB value was selected or even the theoretical rationale appears to be absent from the literature. A similar and relevant clinical question to be answered with this retrospective analysis is whether interoctave thresholds can be predicted from the thresholds of the adjacent or bounding octave frequencies instead of measured, which would save the clinical audiologist valuable minutes during an audiometric exam. Prior to addressing the aforementioned questions, an understanding of the relations among the thresholds of the bounding octave frequencies and the characteristics of the interoctave frequency thresholds are examined.

Octave Frequency Thresholds

The mean right-ear audiogram for the participants is shown in Figure 1 with the data for both ears listed in Table S1, supplemental to the online version of this article, which also lists the number of participants at each frequency that ranged in the right ear from 388,868 at 1500 Hz to 987,757 at 500 Hz. In all probability, this range in the number of participants included in each mean threshold accounts for the slight irregularities observed in the pure-tone threshold function in Figure 1. The audiometric configuration portrays a mild-to-moderate, high-frequency, sensorineural hearing loss that is reflective of the majority of cases included in the sample. Less prevalent audiometric configurations like low-frequency hearing loss and notched audiograms are obscured by the more prevalent audiometric configuration (Wilson and McArdle, 2013). The mean thresholds for the left and right ears in the low-frequency range (250–1000 Hz) are within 0.5 dB, whereas in the higher frequencies the mean thresholds for the left ear are

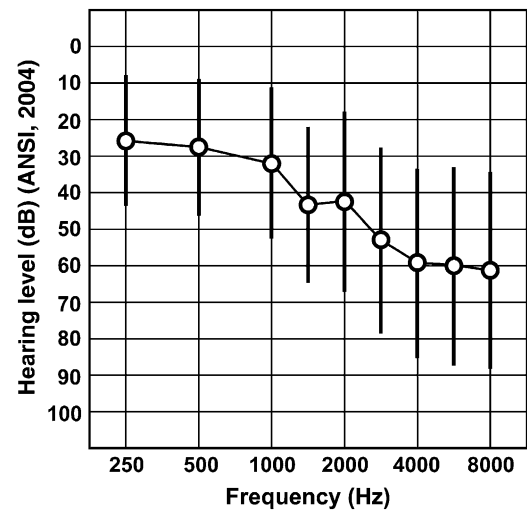


Figure 1. Mean right-ear audiogram from the pool of the participants after the data were cleaned as described in the text. The interoctave frequency data are plotted at their logarithmic coordinates. At most octave frequencies >980,000 participants were involved. The vertical bars represent ± 1 SD.

1–2 dB higher (poorer) than the corresponding mean thresholds for the right ear (Table S1). This relation between the left- and right-ear thresholds was noted early on by Richardson (1879) and in subsequent large-scale studies (e.g., Corso, 1963; Chung et al, 1983; Pirilä et al, 1992; Cruickshanks et al, 1998).

The basic descriptive analyses of the demographic and threshold data by ear are listed in Table 1 for the three interoctave frequencies (1500, 3000, and 6000 Hz).³ Inclusion in any of the six categories (two ears by three interoctave frequencies) required the presence of thresholds for the two bounding octave frequencies and the interoctave frequency, which accounts for the different ages and numbers (n 's) for each of the categories. First, the corresponding data for the two ears are all very similar with mean threshold differences ranging from 0 to 2.2 dB. Second, as the categories progressed from the lower frequencies to the higher frequencies, as expected there was a corresponding increase in the mean thresholds. Additionally, for each set of threshold data, there was a direct relation between the test frequency and the threshold (the higher the frequency, the higher [poorer] the threshold). The spread between the two bounding octave frequency thresholds ranged from ~ 20 dB at 1500 and 3000 Hz to ~ 5 dB at the 6000 Hz. Third, the differences between the interoctave threshold and the two bounding octave frequency thresholds also provide different patterns. At 1500 Hz, the mean interoctave frequency threshold is about midway between the two octave frequency mean thresholds with the difference between the interoctave threshold and the lower-frequency threshold (11–12 dB) slightly larger than the difference observed with

Table 1. Mean Ages (years) and Mean Pure-Tone Thresholds (dB HL) for the Participants along with the SDs (dB) for the Various Combinations of Test Frequencies and Ear

Left Ear					Right Ear			
1500 Hz	Age	1000 Hz	1500 Hz	2000 Hz	Age	1000 Hz	1500 Hz	2000 Hz
Mean	69.5	32.7	44.4	54.8	69.6	32.5	43.2	53.0
SD	12.8	17.8	20.3	20.5	12.9	17.6	20.2	20.9
<i>n</i>	411,168				385,599			
3000 Hz	Age	2000 Hz	3000 Hz	4000 Hz	Age	2000 Hz	3000 Hz	4000 Hz
Mean	65.2	43.1	54.7	61.1	65.3	41.0	52.5	59.3
SD	15.9	23.3	24.0	24.7	15.9	23.1	24.4	25.4
<i>n</i>	904,930				907,619			
6000 Hz	Age	4000 Hz	6000 Hz	8000 Hz	Age	4000 Hz	6000 Hz	8000 Hz
Mean	63.3	56.7	59.3	60.9	63.3	54.8	57.7	59.9
SD	16.2	24.2	25.1	26.7	16.1	24.7	25.6	27.2
<i>n</i>	642,980				647,547			

the higher bounding frequency (10 dB). At 3000 Hz, the mean lower-frequency, interoctave frequency threshold difference (12 dB) is about twice as large as the mean higher-frequency threshold difference (6–7 dB). At 6000 Hz, the differences between the mean interoctave frequency thresholds and either of the mean bounding octave frequency thresholds is small and essentially the same on both sides of the interoctave frequency (2–3 dB). As is often the case with mean data, important differences among conditions can be obscured, which will become apparent in the subsequent analyses. Finally from the data in Table 1, there is a noticeable difference in the mean ages across the three interoctave frequency categories that decrease from the oldest at 1500 Hz to the youngest at 6000 Hz. These various differences among the data in Table 1 are elaborated upon in the following sections of the article that consider the octave-frequency thresholds and then the interoctave frequency thresholds and the relations among them.

Relations among the Octave-Frequency Thresholds

Before considering the relations among the thresholds of the three frequencies (i.e., the two bounding octave frequencies and the interoctave frequency) associated with each of the three interoctave frequencies (1500, 3000, and 6000 Hz), it is instructive to examine the relations between thresholds in the three sets of bounding frequencies (1000 and 2000 Hz; 2000 and 4000 Hz; 4000 and 8000 Hz). In Table 2 the percent distributions of the absolute threshold differences are listed with the subtotals for the <20 dB differences and the ≥20 dB differences also included. Remember that the octave-frequency thresholds were included in these analyses only if the interoctave threshold was measured. (Note: this dichotomy at 20 dB is based on

the historical record reviewed earlier.) The majority of the 1000–2000 Hz threshold differences (63.6 and 61.0%) from the 411,168 and 385,599 participants, respectively, were ≥20 dB, whereas the majority of the 4000–8000 Hz threshold differences (74.8 and 72.3%) from 642,980 and 647,547 participants were <20 dB. The 2000–4000 Hz threshold differences from 904,000+ audiograms were about equally divided about the 20 dB delimiter. Different reasons probably account for the three distributions just described. Obviously from the relatively small number of thresholds included in the 1000–2000 Hz comparison in Table 2, the 1500 Hz interoctave threshold was not measured as often as were the higher interoctave frequency thresholds. The following two reasons probably account for the diminished number: (1) the pure-tone guidelines do not suggest testing 1500 Hz routinely (e.g., ASHA, 2005), and (2) typically the threshold difference between 1000 and 2000 Hz is insufficient (i.e., <20 dB) to trigger testing the interoctave frequency when following the 20 dB difference rule. Support for this comes from the report on 744,553 veterans (Wilson and McArdle, 2013) in which the mean 2000 Hz threshold was about 10 dB higher (poorer) than the mean 1000 Hz threshold, whereas the mean 4000 Hz threshold was about 20 dB higher than the mean 2000 Hz threshold. This second point probably accounts for the majority of the 1000–2000 Hz threshold differences being ≥20 dB; that is, 1500 Hz was tested most often when the 1000–2000 Hz threshold difference was ≥20 dB, which biased the 1500 Hz data. These threshold relations are consistent with the mean age of the participants in the 1000–2000 Hz data set being older than the participants in the other data categories (Table 1). Here the underlying assumption is that the older participants have high-frequency hearing loss that starts in the lower-frequency range and is steeper than the high-frequency hearing loss

Table 2. Percent of Absolute Threshold Differences between the Octave Frequency Pairs (in dB) for the Left Ears and Right Ears

dB Difference	1000 and 2000 Hz		2000 and 4000 Hz		4000 and 8000 Hz	
	LE	RE	LE	RE	LE	RE
0	5.5	6.3	9.2	9.3	14.4	13.7
5	9.9	11.1	17.0	16.8	25.6	24.6
10	9.2	9.5	14.9	14.5	20.2	19.5
15	11.8	12.1	12.9	12.6	14.5	14.5
Total <20	36.4	39.0	54.0	53.2	74.8	72.3
20	15.7	16.4	11.4	11.3	10.3	10.9
25	13.4	13.4	9.3	9.3	6.4	6.9
30	10.5	10.2	7.3	7.5	3.8	4.3
35	8.1	7.5	5.6	5.7	2.2	2.5
40	5.9	5.3	4.1	4.2	1.2	1.5
45	4.2	3.6	2.9	3.0	0.6	0.8
50	2.7	2.2	2.0	2.1	0.3	0.4
>50	3.1	2.3	3.4	3.6	0.3	0.4
Total ≥20	63.6	61.0	46.0	46.8	25.2	27.7
<i>n</i>	411,168	385,599	904,930	907,619	642,980	647,547

from younger participants. Recall from Table 1 that the oldest age group was associated with the 1000–2000 Hz data set.

Finally, of the 575,172 left ears on which 1500 Hz thresholds were not obtained, 93% of the octave threshold differences were <20 dB. Specifically, in absolute values 23% of the octave thresholds had no threshold difference, 35.3% had a 5 dB difference, 22.4% had a 10 dB difference, and 12.2% had a 15 dB difference. Thus, only 7% of the left ears on which 1500 Hz thresholds were not obtained had octave frequency thresholds that were ≥20 dB. Similar findings were observed for the right ears with 5.2% not tested when the octave thresholds were ≥20 dB. Collectively, these findings at 1500 Hz coupled with the data in Table 2 suggest that audiologists followed the 20 dB rule the majority of the time.

In contrast to the 1000–2000 Hz data, the higher frequency data sets suggest that the interoctave frequencies were tested more often, evidenced by the number of participants involved, which increased from roughly 400,000 at 1000–2000 Hz to over 900,000 at 2000–4000 Hz to about 645,000 at 4000–8000 Hz. As can be seen in Table 2, routinely testing the two higher interoctave frequencies produced an increasingly larger proportion of octave threshold differences that were <20 dB, ranging from 53–54% at 2000–4000 Hz to 72–75% at 4000–8000 Hz. The percent of differences is high in the 4000–8000 Hz condition because on average the threshold difference between 4000 and 8000 Hz is not very large, on the order of 5 dB (Table 1). In the previously mentioned study of 744,553 veterans, the mean thresholds for 4000 and 8000 Hz differed by <5 dB. The number (*n*) of audiograms involved at each of the three frequency sets listed in Tables 1 and 2 differ

substantially. The relatively small *n* for the 1000 and 2000 Hz comparison was previously considered. The number of participants at 4000 and 8000 Hz is about 260,000 less than at 2000 and 4000 Hz, which is probably the result of fewer high-frequency thresholds being measurable, especially in the older participants at 8000 Hz. This reasoning also probably contributes to the mean age in the 4000–8000 Hz category being lower than the mean age in the other two categories (Table 1).

The previous analyses considered the octave frequency threshold differences in absolute terms. The left-ear and right-ear data in Table 3 are the distributions (*n* and %) of the slopes of the octave-frequency thresholds that bound the interoctave frequencies. For example, if the threshold at 1000 Hz were lower (better) than the threshold at 2000 Hz, then the slope of the line connecting the two octave thresholds would be negative. Consider the three sets of data associated with the “Overall” descriptor in Table 3 (the other data will be considered in the following section). First, although the number of participants in the corresponding categories for the two ears can differ substantially (e.g., 365,805 left ears and 333,766 right ears for the “Slope” category at 1500 Hz), the relations between the two ears in percent are similar (e.g., 89.0 and 86.6%). Second, there is an inverse relation between the interoctave frequency and the percent of negative slopes, exemplified by the left-ear data that decreased from 89.0% (1500 Hz) to 83.8% (3000 Hz) to 53.5% (6000 Hz). Around the 1500 and 3000 Hz interoctaves, the percent of positive slopes and zero slopes range from 5.6 to 7.1%, whereas with 6000 Hz there are appreciably more positive slopes (30–32%), which may be reflecting the audiometric notching that often occurs in the higher frequencies (Wilson, 2011; Wilson and McArdle, 2013).

Table 3. Distributions (*n* and %) of the Relation between the Two Octave Frequency Thresholds Bounding Each of the Inter octave Frequencies for the Two Ears with Respect to the Slope of the Line between the Octave Frequency Thresholds

		Left Ear				Right Ear			
		–Slope	+Slope	0 Slope	Totals	–Slope	+Slope	0 Slope	Totals
1500 Hz (1000 Hz minus 2000 Hz)									
Overall	<i>n</i>	365,805	22,929	22,434	411,168	333,766	27,570	24,263	385,599
	%	89.0	5.6	5.5	100	86.6	7.1	6.3	100
Inside	<i>n</i>	342,785	19,200	10,804	372,789	312,731	23,397	12,041	348,169
	%	92.0	5.2	2.9	100	89.8	6.7	3.5	100
Outside	<i>n</i>	23,020	3,729	11,630	38,379	21,035	4,173	12,222	37,430
	%	60.0	9.7	30.3	100	56.2	11.1	32.7	100
3000 Hz (2000 Hz minus 4000 Hz)									
Overall	<i>n</i>	758,431	63,385	83,114	904,930	758,774	64,789	84,056	907,619
	%	83.8	7.0	9.2	100	83.6	7.1	9.3	100
Inside	<i>n</i>	674,230	51,253	38,839	764,322	674,688	52,186	38,579	765,453
	%	88.2	6.7	5.1	100	88.1	6.8	5.0	100
Outside	<i>n</i>	84,201	12,132	44,275	140,608	84,086	12,603	45,477	142,166
	%	59.9	8.6	31.5	100	59.1	8.9	32.0	100
6000 Hz (4000 Hz minus 8000 Hz)									
Overall	<i>n</i>	343,734	206,704	92,542	642,980	361,983	196,779	88,785	647,547
	%	53.5	32.1	14.4	100	55.9	30.4	13.7	100
Inside	<i>n</i>	265,982	162,240	32,750	460,972	280,760	153,485	31,313	465,558
	%	57.7	35.2	7.1	100	60.3	33.0	6.7	100
Outside	<i>n</i>	77,752	44,464	59,792	182,008	81,223	43,294	57,472	181,989
	%	42.7	24.4	32.9	100	44.6	23.8	31.6	100

Note: The data are given for overall group at each inter octave frequency and for the two subgroups when the inter octave threshold was inside the range of thresholds for the bounding octave frequencies (Inside) and when the inter octave threshold was outside the range of thresholds for the bounding octave frequencies (Outside). A negative slope occurred when the threshold of the lower boundary frequency was lower (better) than the threshold of the upper boundary frequency.

Overall, then, the majority of thresholds for the octave pairs demonstrate lower (better) thresholds for the lower bounding frequency than for the higher bounding frequency, which was a finding reflected by the mean threshold data in Table 1.

Inter octave Thresholds

When considering the auditory thresholds at the inter octave frequencies (1500, 3000, and 6000 Hz), audiologists typically think of the inter octave threshold as being somewhere between the thresholds of the two bounding octave frequencies. As the data below will demonstrate, this intuitive concept is not entirely factual. Because the threshold at an inter octave frequency is one of three thresholds required for the paradigm evaluation, the *median* metric is the logical choice for evaluating and describing the relations among the three threshold measures involved with each inter octave frequency. For the purposes considered here, if the threshold of the inter octave frequency is also the median of the three thresholds, then the inter octave threshold is equal to or *between* the range of thresholds for the bounding octave frequencies (i.e., *inside* the range of thresholds for the bounding octave frequencies), which is considered a systematic relation. Con-

versely, if the threshold of the inter octave frequency is not the median of the three thresholds, then the threshold of the inter octave frequency is *outside* the range of thresholds for the bounding octave frequencies, which is considered a nonsystematic relation.

Consider the “Inside” and “Outside” data in Table 3. The percentages for the three inter octave frequency thresholds in the Inside category for the most part follow the patterns in the Overall category, which is to be expected as the number of participants in the Inside category represent 70–90% of the totals. Consider again the 1500 Hz data for the left ear. The percents for the three slope categories were 89.0, 5.6, and 5.5 (Overall) and 92.0, 5.2, and 2.9 (Inside). Another consistency across the three inter octave frequencies is roughly one-third of the participants in the Outside category had slopes between octave thresholds that were zero, meaning that the thresholds for the bounding octave frequencies were the same. In terms of the hearing level (HL; ANSI, 2004) of these equal octave thresholds, the initial thought was that they were at the extremes of the hearing loss range, i.e., 0–20 dB HL or 100–110 dB HL. When the distributions of the threshold hearing levels were plotted (not shown), however, it was obvious that this line of reasoning was only partially correct. The distributions were the same for the two ears at each of the

interoctave frequencies but different across the interoctave frequencies with each frequency having obvious clusters in the distributions. At 1500 Hz, 50–55% of the equal octave thresholds were in the 10–30 dB HL range. At 3000 Hz, the distributions were bimodal with 30–35% of the equal octave thresholds in the 5–20 dB HL range and 30–35% in the 60–75 dB HL range. At 6000 Hz, 43–46% of the equal octave thresholds were in the 60–80 dB HL range. The clusters in the lower hearing loss range at 1500 and 3000 Hz are reflecting thresholds with little to no hearing loss, whereas the clusters in the higher hearing loss range at 3000 and 6000 Hz are reflecting thresholds that tend to flatten and are near the upper limit of hearing loss with the majority of patients. Only a few of the equal octave frequency thresholds (<1%), even for 4000 and 8000 Hz, were in the 100–110 dB HL range.

The data from Table 3 are recast in Table 4 to list the number (*n*) and percent of left and right ears that had interoctave frequency thresholds that were either inside or outside the range of thresholds for the bounding frequencies at each of the six threshold sets. Consider the 1500 Hz total data for the left ear in Table 4. With the 411,168 participants, 372,789 of the interoctave thresholds (90.7%) were inside the range of thresholds for 1000 and 2000 Hz. Conversely, 9.3% of the interoctave frequency thresholds were outside the threshold bounds set by the adjacent octave-frequency thresholds. As the interoctave frequency increased from 1500 to 6000 Hz, the percent of thresholds at the interoctave frequencies that were outside the threshold bounds of the respective octave frequencies increased from 9.3–9.7% (1500 Hz) to 15.5–15.7% (3000 Hz) to 28.1–28.3% (6000 Hz).

Several analyses were pursued to gain insight into the dynamics involved when the threshold of the inter-

octave frequency was outside of the threshold bounds of the octave frequencies, which is a focus on the data in the Outside rows in Table 3. First, the data were parsed according to which of the two bounding octave-frequency thresholds was closer arithmetically to the interoctave threshold. The data in this form are presented in Tables S2–S4, supplemental to the online version of this article. In each table, the dB difference was determined by subtracting the interoctave threshold from the octave frequency threshold that was closer arithmetically to the interoctave threshold. At 1500 Hz (Table S2), 29.9–30.2% of the interoctave thresholds were closer to the 1000 Hz threshold than to the 2000 Hz threshold; 37.1–39.8% of the interoctave thresholds were closer to the 2000 Hz threshold than to the 1000 Hz threshold; and 30.3–32.7% of the interoctave thresholds were equidistant from the two octave thresholds. The 3000 Hz data (Table S3) showed a different relation with 21.1–22.6% of the interoctave thresholds closer to the 2000 Hz threshold than to the 4000 Hz threshold; 45.5–47.4% of the interoctave thresholds closer to the 4000 Hz threshold than to the 2000 Hz threshold, and ~32.0% of the interoctave thresholds equidistant from the two octave thresholds. The 3000 Hz data indicate that the 3000 Hz thresholds are more closely associated with the 4000 Hz thresholds than with the 2000 Hz thresholds. The 6000 Hz data (Table S4) were almost equally divided in thirds with 32.7–33.3% of the interoctave thresholds closer to the 4000 Hz threshold than to the 8000 Hz threshold; 34.4–35.2% of the interoctave thresholds closer to the 8000 Hz threshold than to the 4000 Hz threshold; and 31.6–32.9% of the interoctave thresholds equidistant from the two octave thresholds. The fact that the 3000 Hz data are different from the other two datasets is not surprising as 3000 Hz is on a more dynamic portion of the audiogram than either 1500 or 6000 Hz. One final note about the data in Tables S2–S4 deserves mention. In each of the distributions, the vast majority of the differences between the interoctave threshold and the closer of the octave-frequency thresholds were ± 5 dB. With 1500 Hz, 85% of the threshold differences were ± 5 dB; with 3000 Hz, 82% were ± 5 dB; and with 6000 Hz, 69% were ± 5 dB. Some of these 5 dB differences are real threshold differences, and some are simply the result of measurement error that can occur during threshold testing. In any event, had these 5 dB differences been 0 dB, then the associated interoctave threshold would be inside the threshold bounds of the adjacent octave frequencies and the relation among the three-frequency thresholds considered systematic.

The bivariate plots in Figure 2 provide a visual summary for the left ear of the relation between the mean threshold of the bounding octave frequencies (ordinate), which is the predicted threshold, and the threshold of the interoctave frequency (abscissa), which is the measured

Table 4. Number and Corresponding Percents of Left-Ear and Right-Ear Inter octave Frequency Thresholds That Were Inside the Range of Thresholds for the Bounding Octave Frequencies (Inside) and When the Inter octave Threshold Was Outside the Range of Thresholds for the Bounding Octave Frequencies (Outside)

	Inter octave frequency					
	1500 Hz		3000 Hz		6000 Hz	
	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%
Left ear						
Inside	372,789	90.7	764,322	84.5	460,972	71.7
Outside	38,379	9.3	140,608	15.5	182,008	28.3
Total	411,168		904,930		642,980	
Right ear						
Inside	348,169	90.3	765,453	84.3	465,558	71.9
Outside	37,430	9.7	142,166	15.7	181,989	28.1
Total	385,599		907,619		647,547	

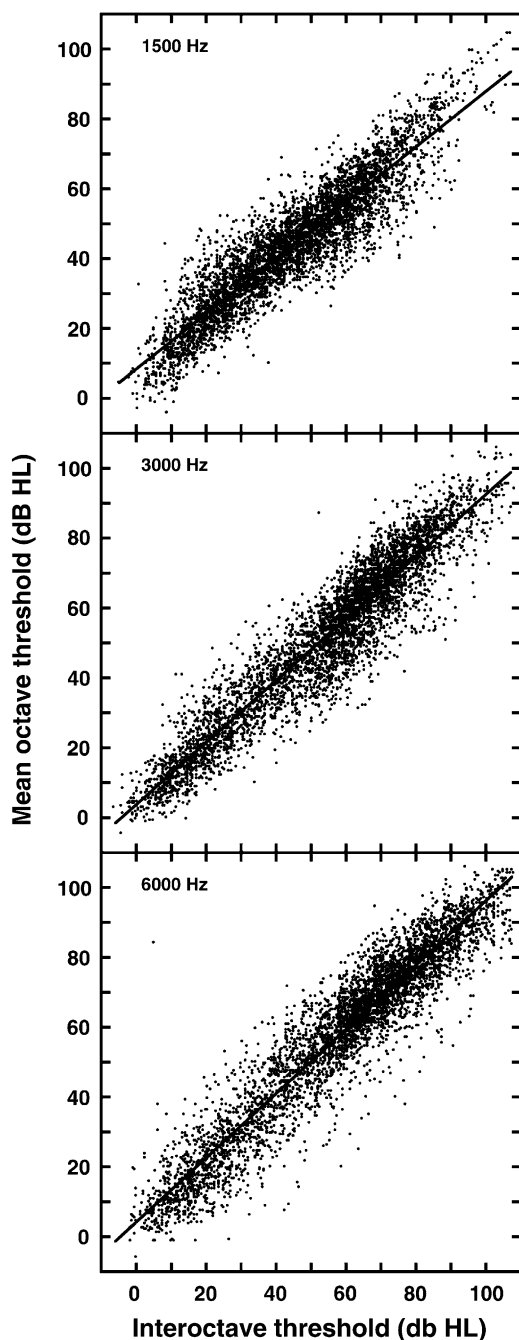


Figure 2. Bivariate plots (left ear) of the interoctave frequency threshold (abscissa) and the mean octave frequency threshold for a sample of 5000 participants at each of the three interoctave frequencies. Linear regressions are shown for each set of data. The data were sampled randomly from the 411,168 (1500 Hz), 904,930 (3000 Hz), and 642,980 (6000 Hz) participants. For graphic clarity, the x and y data independently were jittered using an additive algorithm from -2.4 to 2.4 in 0.1 steps that was applied randomly.

threshold. Because the resolution of a plot containing 400,000 to 900,000 datum points is zero, a random sample of 5000 data sets was made of the data from each of the three interoctave frequencies and plotted using a jittered, additive algorithm to enhance clarity. Minimal

differences were found between the linear regressions obtained for the random samples and the linear regressions for the entire data samples, thereby ensuring the random samples used in the figure were representative of the complete data set. In the figure the linear regressions for the entire samples are plotted. The R^2 values for the two ears were the same at each frequency, ranging from 0.85 (1500 Hz) to 0.91 (6000 Hz). The lower R^2 at 1500 Hz probably is reflecting the higher proportion of ≥ 20 dB octave frequency threshold differences than was observed at the other two interoctave frequencies (Table 2). Conversely, the higher R^2 at 6000 Hz probably is reflecting the lower incidence of < 20 dB octave frequency threshold differences than was observed at the other two interoctave frequencies. The equations for the linear regressions in Figure 2 were these:

$$1500 \text{ Hz, } y = 8.5941 + 0.7916x;$$

$$3000 \text{ Hz, } y = 3.4309 + 0.8894x; \text{ and}$$

$$6000 \text{ Hz, } y = 4.1247 + 0.9228x.$$

The direct relation between the slope of the regression and the interoctave frequency is apparent from the equations. As the frequency increased, the slope became steeper, only approaching unity at 6000 Hz. An underlying reason that the slopes are < 1 might be related to the systematic difference between thresholds for the interoctave frequency (arithmetic) and for the half-octave frequency (logarithmic) that is discussed in Appendix A. Additionally, the slopes are influenced by the higher density of datum points in the higher threshold values for the higher interoctave frequency conditions. For 1500 Hz, there were few datum points in the 80–100 dB HL range. The equations for the right-ear data (not shown) were almost identical to the equations for the left ear.

Predicting Interoctave Frequency Thresholds

A question of interest is how accurately does the mean threshold of the bounding octave frequencies predict the threshold of the interoctave frequency? The mean of the bounding octave thresholds minus the interoctave threshold provides this information. The detailed distributions for the threshold differences are listed for the three interoctave frequencies and each ear in Tables S5–S7, supplemental to the online version of this article; these data for the left ear are plotted in Figure 3. Cumulative distributions of the threshold differences (in percent) are provided in Table 5. The data in both the figure and tables are presented for three conditions: (1) when the threshold difference between bounding octaves is ≥ 20 dB (triangles), (2) when the threshold difference between bounding octaves is < 20 dB (squares), and (3) when the two data sets are combined (circles). Several features/relations are noticeable in Figure 3. In general, the

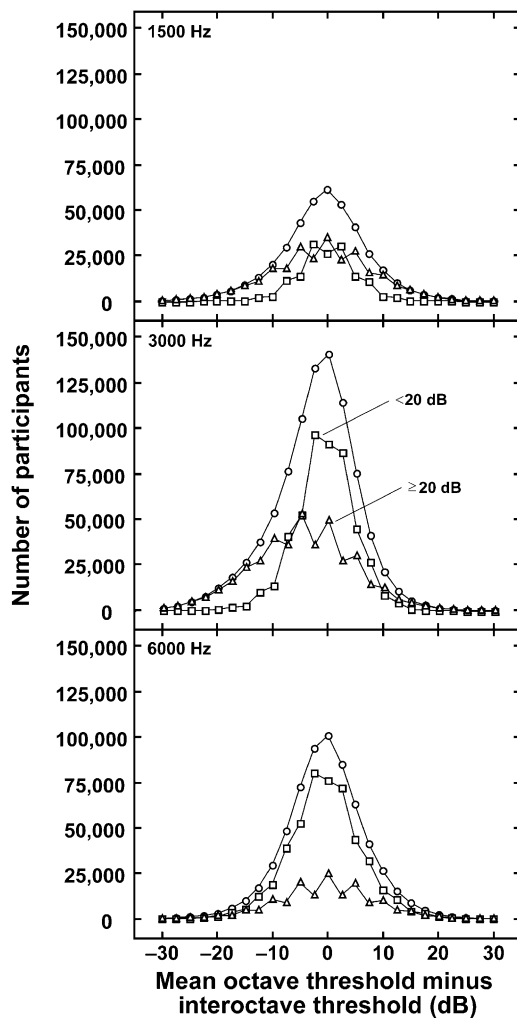


Figure 3. Left-ear distributions of the difference between the threshold of the interoctave frequency and the mean threshold of the two respective bounding octave frequencies are shown for three conditions: when the difference between the bounding octave frequency thresholds was ≥ 20 dB (triangles), when the difference between the bounding octave frequency thresholds was < 20 dB (squares), and both groups combined (circles).

distributions are fairly normal. At the two lower interoctave frequencies, the ≥ 20 dB data are more broadly distributed than are the < 20 dB data. The ≥ 20 dB data are multip peaked. This modulation reflects a systematic mathematical uniqueness of the second order effect (i.e., a threshold difference) that involves the 5 dB step size of the psychophysical procedure that can include a 2.5 dB component when numbers ending in 0 and 5 are averaged.

From the data in Table 5, for corresponding conditions the distributions for the left and right ears are the same with the largest difference between ears (1.9%) at 1500 Hz, ± 5 , "Combined" datum point. For each of the six conditions (two ears by three frequencies), 62.0–64.9% of the cases had a threshold for the interoctave frequency that was within ± 5 dB of the

Table 5. Cumulative Distributions in Percent of the Mean Octave Frequency Threshold Minus the Interoctave Frequency Threshold Listed for the Octave Threshold Differences ≥ 20 dB, < 20 dB, and Both Combined

Difference (dB)	Left ear			Right ear		
	≥ 20 dB	< 20 dB	Combined	≥ 20 dB	< 20 dB	Combined
1500 Hz						
0	13.5	17.6	15.0	14.2	18.0	15.7
± 5	53.2	77.4	62.0	54.9	78.0	63.9
± 10	78.4	96.1	84.9	80.3	96.3	86.6
± 15	91.7	99.4	94.5	92.9	99.4	95.5
± 20	97.4	99.9	98.3	98.0	99.9	98.7
± 25	99.4	100.0	99.6	99.6	100.0	99.7
3000 Hz						
0	12.0	18.7	15.6	11.8	18.6	15.4
± 5	47.5	76.5	63.2	47.5	76.1	62.7
± 10	72.4	95.1	84.7	72.6	94.9	84.5
± 15	87.4	99.0	93.7	87.7	99.0	93.7
± 20	95.1	99.8	97.6	95.4	99.8	97.7
± 25	98.5	99.9	99.3	98.6	99.9	99.3
6000 Hz						
0	15.4	15.9	15.8	15.0	15.6	15.5
± 5	56.2	67.9	64.9	54.8	67.0	63.6
± 10	80.7	90.1	87.7	79.4	89.5	86.7
± 15	92.6	97.2	96.0	91.8	96.9	95.5
± 20	97.3	99.2	98.7	96.9	99.1	98.5
± 25	99.0	99.7	99.6	98.9	99.7	99.5

Note: The distributions for the raw left-ear data are plotted in Figure 3.

mean threshold of the two bounding octave frequencies. If the criterion were increased to ± 10 dB, then about 85% of the cases would be included. From the data in the table and as can be seen in Figure 3, the degree of agreement between the interoctave threshold and the mean bounding octave threshold varies depending on the magnitude of the difference between the octave frequency thresholds. As one would expect, when the difference between the octave frequency thresholds increased, the prediction of the interoctave frequency threshold was less precise. Consider for example the ± 5 dB data in Table 5 for the left ear, at 1500 Hz. When the octave threshold difference was ≥ 20 dB, 53.2% of the thresholds were within the ± 5 dB criterion. In contrast, when the octave threshold difference was < 20 dB, the agreement between the two thresholds increased substantially to 77.4%. Similar relations can be observed with the other ear/frequency conditions. Finally from Table 5, a comparison can be made with similar 3000 Hz data from 2170 ears reported recently by Gurgel et al (2012), who compared estimates of the interoctave frequency threshold (the average of the two bounding octave frequency thresholds) with measures of the interoctave threshold. They observed that with 72% of the cases the agreement between the estimated and measured thresholds was ± 5 dB, increasing progressively to 91 and 99% agreements when using ± 10 dB and ± 20 dB

Table 6. Number and Percent of Participants Listed According to the Absolute Octave Frequency Threshold Difference

Absolute octave threshold difference (dB)	<i>n</i>	Percent of sample	Threshold agreement (dB)				
			±5	±10	±15	±20	±25
0	83,114	9.2	90.6	98.4	99.7	99.9	100.0
5	154,184	17.0	74.0	95.6	99.2	99.8	99.9
10	134,779	14.9	85.0	97.2	99.4	99.9	100.0
15	116,824	12.9	60.0	89.8	97.9	99.5	99.9
20	102,780	11.4	71.2	92.0	98.3	99.6	99.9
25	84,459	9.3	44.7	77.0	93.3	98.5	99.7
30	66,335	7.3	54.9	80.3	94.1	98.8	99.7
35	50,479	5.6	33.1	60.9	82.3	94.7	99.0
40	36,839	4.1	40.8	64.5	83.8	95.3	99.2
45	26,087	2.9	24.0	47.3	68.5	86.3	96.3
50	18,047	2.0	31.8	52.8	72.5	87.9	97.1
55	12,178	1.3	19.1	38.5	58.2	76.8	90.4
60	8,023	0.9	26.8	45.1	64.3	80.9	92.7
65	4,956	0.5	16.5	33.7	52.2	70.9	85.3
70	3,059	0.3	23.0	41.0	58.6	74.0	86.8
75	1,648	0.2	14.7	28.9	45.0	62.5	77.7
80	759	0.1	23.6	38.1	54.4	70.4	83.8
85	287	0.0	13.9	29.3	40.4	57.8	73.2
90	77	0.0	19.5	33.8	45.5	59.7	75.3
95	16	0.0	6.3	25.0	50.0	62.5	62.5
Totals	904,930	100.0					

Note: Within each of the difference categories, the cumulative percent of participants are listed according to the difference between the mean octave frequency threshold and the interoctave frequency threshold. The data are for the 904,930 left ears at 2000, 3000, and 4000 Hz.

criterion, respectively. For the three decibel criterion ranges, the current 3000 Hz data for the left ear in Table 5 had 63.2%, 84.7%, and 97.6% agreements, respectively, between the estimated and measured interoctave frequency thresholds. This is reasonable congruence between the studies considering that the distribution of the octave frequency threshold differences was not reported by Gurgel et al.

The measured and predicted interoctave thresholds for both the right and left ears at each of the three frequencies (1500, 3000, and 6000 Hz) were subjected to a repeated measures analysis of variance using the General Linear Model. As expected, given the large sample size, all of the main effects and interactions were statistically significant ($p < .001$) even though absolute mean differences between predicted and measured thresholds were <1 dB. To examine further whether the difference between the octave thresholds could predict when the interoctave threshold needs to be measured, a repeated measures analysis of variance was completed with threshold as the within subjects variable (two levels, measured threshold and predicted threshold) and the bounding octave frequency threshold differences as a between subjects factor. Again, given the large sample size, even when the difference between the bounding octave thresholds was 0, the difference between the measured and predicted interoctave threshold was a statistically significant with a difference of <1 dB. These statistically significant dif-

ferences lack clinical relevance given all the threshold differences were <3 dB, which is smaller than the acceptable range of measurement error (± 5 dB). In addition, the partial eta squared (η^2) values were insignificant (< 0.07) except for the main effect of frequency (0.29). When making a decision for an individual patient as to whether interoctave thresholds need to be measured, the data presented in Table 6 provide a better framework for making an evidence-based decision.

The 3000 Hz data from the left ear listed in Table 5 are detailed in more depth in Table 6 (the corresponding data from the right ear were the same). These data were selected because the three involved frequencies (2000, 3000, and 4000 Hz) provided a substantially larger database than was available from the 1500 Hz and 6000 Hz interoctave frequency sets. In the table for each absolute octave-threshold difference (0 to 95 dB) the sample size and percent of the sample are listed along with the cumulative percent of participants within the five ranges of threshold agreement between the thresholds for the mean octave frequencies and for the interoctave frequency. For example, when the threshold difference between the octave frequencies was 5 dB ($n = 154,184$), 74.0% of the participants had interoctave thresholds that were within ± 5 dB of the mean threshold for the bounding octave frequencies. When the agreement criterion was increased to ± 10 dB, 95.6% of the participants were included. In contrast, when the threshold difference between the octave frequencies

was 50 dB ($n = 18,047$), 31.8% of the participants had interoctave thresholds that were within ± 5 dB of the mean threshold for the bounding octave frequencies, which increased to 52.8% for the ± 10 dB criterion, etc. This is another way to illustrate the inverse relation between the threshold difference of the bounding octave frequencies and their predictive accuracy of the interoctave threshold, that is, as the octave frequency threshold differences increase the accuracy of predicting the threshold of the interoctave frequency decreases. From the data in the table it is easy to determine the accuracy with which the interoctave frequency thresholds can be predicted as the midpoint between the two octave thresholds. Overall, the data in Table 6 indicate good agreement (i.e., ± 5 dB and ± 10 dB) between the mean octave frequency threshold and the interoctave frequency threshold when the thresholds for the octave frequencies are ≤ 20 dB. Thus, the majority of time, the mean of the octave frequency thresholds can be used to predict the interoctave threshold with good precision when there is a 20 dB or less difference between the thresholds of the bounding octave frequencies. When the octave threshold difference is ≥ 25 dB, the accuracy of the prediction is progressively diminished. These data confirm that the 20 dB rule is appropriate as an indicator of the need to establish the interoctave frequency threshold and could even be considered a bit conservative as using 25 dB as the critical difference would provide essentially the same result.

CONCLUSIONS

The results of this retrospective analysis lend credence to the age-old adage that interoctave thresholds should be measured if there is a 20 dB difference or greater between thresholds at the adjacent octave frequencies. The following conclusions from these retrospective analyses can be drawn:

1. The majority of thresholds for the bounding octaves demonstrate lower (better) thresholds for the lower frequency than for the higher frequency. At 2000 Hz, $\sim 86\%$ of the thresholds were higher (poorer) than the thresholds at 1000 Hz; $\sim 83\%$ of the thresholds at 4000 Hz were lower than the thresholds at 2000 Hz; and $\sim 54\%$ of the thresholds at 8000 Hz were lower than the thresholds at 4000 Hz.
2. The majority of the interoctave frequency thresholds were equal to or between the thresholds of the two bounding octave frequencies, ranging from 90% at 1500 Hz to 84% at 3000 Hz to 72% at 6000 Hz, the implication being that the threshold of the interoctave frequency is not always between the thresholds of the bounding octave frequencies.
3. When the interoctave threshold was not equal to or between the thresholds of the two bounding octave

frequencies, the vast majority of interoctave thresholds were within ± 5 dB of the mean threshold of the bounding octave frequencies, specifically 85% at 1500 Hz, 82% at 3000 Hz, and 69% at 6000 Hz.

4. The mean threshold of the bounding octave frequencies provides a good estimate of the threshold of the interoctave frequency. As the difference between octave frequency thresholds increases, however, the accuracy of predicting the interoctave threshold decreases.
5. Based on the 2000–4000 Hz data, when the octave frequency threshold difference is < 20 dB the mean of the octave frequency thresholds is an accurate predictor of the threshold for the interoctave frequency 60–90% of the time (± 5 dB) or 90–98% of the time (± 10 dB). The current data support the so-called ≥ 20 dB rule for testing interoctave frequency thresholds and suggest that the rule could be increased to ≥ 25 dB with little adverse effect.

Collectively, the data and analyses presented provide guidance to audiologists when deciding whether to establish thresholds for an interoctave frequency. Given that the majority of interoctave frequency thresholds were equal to or between the thresholds of the two bounding octave frequencies, unless there are other medical indicators or hearing-aid fitting requirements that necessitate greater precision, interoctave thresholds may be estimated using the mean threshold of the bounding octave frequencies without much loss of accuracy, especially when the difference between the thresholds for the bounding octave frequencies are small. Although no historical data supporting the infamous 20 dB rule could be found, the data presented in the current analyses suggest that a 20 dB difference between adjacent octave thresholds is a good criterion choice regarding the necessity of establishing threshold for the interoctave frequency.

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NOTES

1. The use of *interoctave* and *intra-octave* deserves comment. To the authors, both terms mean the same thing, just from different points of view. *Interoctave* means between two octaves; for example, 3000 Hz is between 2000 and 4000 Hz. *Intra-octave* means within an octave; for example, 3000 Hz is within the octave spanning 2000 to 4000 Hz. Throughout this manuscript, *interoctave* is used as the arithmetic mean frequency of the adjacent octave

- frequencies. As described in Appendix A, the interoctave frequency is different from the half-octave frequency.
- Over the years a number of descriptors have been used to describe the scientific unit for frequency, including *pitch*, *double vibrations* (d.v.), *vibrations/second* (vib/sec), *cycles, cycles per second* (cps) and *Hertz*. In 1935 the International Electrotechnical Commission (IEC) adapted the meter-kilogram-mass-second (MKS) system of Giorgi as the successor of the centimeter-gram-second (cgs) system that had been adapted in 1881 (Kennelly, 1935). In Kennelly (1935), the unit of frequency (*f*) was designated as "Hertz," which had been proposed in 1930 by the technical Committee on Electric and Magnetic Magnitudes and Units (Ruppert, 1956). The unit was named in honor of Heinrich Rudolf Hertz (1857–1894), who was a German physicist and a student of Helmholtz. This early adaptation of *Hertz* explains the occasional use starting in the 1930s of *Hertz* as the unit of frequency (e.g., Pohlman, 1931, p. 160). Consistent usage of *Hertz* originated with the adaptation of the *Système International d'Unités* (SI) in 1960 that reconfirmed *Hertz* as the frequency unit to be abbreviated *Hz*.
 - Each data set is composed of three thresholds, including the two octave-frequency thresholds that bound the interoctave frequency and the interoctave frequency threshold. To simplify this communication, these three frequencies or three thresholds are referred to throughout the manuscript as *the three frequencies*, *the three-frequency thresholds*, and *the threshold set*.

REFERENCES

- American National Standards Institute (ANSI). (1978) *Methods for Manual Pure-Tone Threshold Audiometry (ANSI S3.21-1978)*. New York: American National Standards Institute.
- American National Standards Institute (ANSI). (2004) *Methods for Manual Pure-Tone Threshold Audiometry (ANSI S3.21-2004)*. New York: American National Standards Institute.
- American National Standards Institute (ANSI). (2010) *Specification for Audiometers (ANSI/ASA S3.6-2010)*. New York: American National Standards Institute.
- American Speech-Language-Hearing Association (ASHA). (1990) *Audiometry Symbols* [Guidelines]. www.asha.org/policy.
- American Speech-Language-Hearing Association (ASHA). (2005) *Guidelines for Manual Pure-Tone Threshold Audiometry* [Guidelines]. www.asha.org/policy.
- American Standards Association. (1951) *American Standard Specification for Audiometers for General Diagnostic Purposes (Z24.5-1951)*. New York: American Standards Association.
- Bickerton RC, Barr GS. (1987) The origin of the tuning fork. *J R Soc Med* 80(12):771–773. www.ncbi.nlm.nih.gov/pmc/articles/PMC1291142/pdf/jrsocmed00168-0057.pdf.
- Bunch CC. (1939) Traumatic deafness. In: Fowler EP, Jr., ed. *Medicine of the Ear*. New York: Thomas Nelson and Sons, 349–367. Reprinted 1970. Translations of the Beltone Institute for Hearing Research 23. Chicago: Beltone Institute for Hearing Research, 9–27.
- Bunch CC. (1943) *Clinical Audiometry*. St. Louis: C. V. Mosby Company.
- Carhart RT. (1970) Introduction. In: Tonndorf J, ed. *Translations of the Beltone Institute for Hearing Research* 23. Chicago: Beltone Institute for Hearing Research, 7–8.
- Chung DY, Mason K, Gannon RP, Willson GN. (1983) The ear effect as a function of age and hearing loss. *J Acoust Soc Am* 73(4):1277–1282.
- Corso JF. (1963) Age and sex differences in pure-tone thresholds. Survey of hearing levels from 18 to 65 years. *Arch Otolaryngol* 77:385–405.
- Council on Physical Therapy. (1939) Minimum requirements for acceptable audiometers. *J Am Med Assoc* 112(8):732. <http://jamanetwork.com/article.aspx?articleid=285292>.
- Cruikshanks KJ, Wiley TL, Tweed TS, et al. (1998) Prevalence of hearing loss in older adults in Beaver Dam, Wisconsin. The Epidemiology of Hearing Loss Study. *Am J Epidemiol* 148(9):879–886.
- Dean SW, Bunch CC. (1919) The use of the pitch range audiometer in otology. *Laryngoscope* 29:453–462.
- Fletcher H. (1934) Loudness, pitch and the timbre of musical tones and their relation to the intensity, the frequency and the overtone structure. *J Acoust Soc Am* 6:59–69.
- Fletcher H, Wegel RL. (1922) The frequency-sensitivity of normal ears. *Proc Natl Acad Sci USA* 8(1):5–6.2. <http://www.pnas.org/content/8/1/5.full.pdf+html>.
- Fowler EP, Jr, Lüscher E. (1950) Report of the standardization sub-committee. *Acta Otolaryngol Suppl* 90:17–20.
- Fowler EP, Wegel RL. (1922) Audiometric methods and their applications. In: *Transactions of the Twenty-Eighth Annual Meeting of the American Laryngological, Rhinological, and Otological Society, Inc. Held in Washington, D.C., May 4th, 5th, and 6, 1922*. New York: American Laryngological, Rhinological, and Otological Society, 98–132. <http://books.google.com/books?hl=en&lr=&id=BQ8hAQAIAAJ&oi=fnd&pg=PA98&dq=fowler+ep&ots=HTazow5E37&sig=ZuM2GMrfBvaRSNghf0Jg10jChK4#v=onepage&q=fowler%20ep&f=false>.
- Gradenigo G. (1913) Suggestions in acoumetry. *Laryngoscope* 23:770–777.
- Green DS. (1972) Pure tone air conduction thresholds. In: Katz J, ed. *Handbook of Clinical Audiometry*. Baltimore: Williams and Wilkins Company, 67–86.
- Gurgel RK, Popelka GR, Oghalai JS, Blevins NH, Chang KW, Jackler RK. (2012) Is it valid to calculate the 3-kilohertz threshold by averaging 2 and 4 kilohertz? *Otolaryngol Head Neck Surg* 147:102–104.
- Guttman J. (1921) A new method of measuring hearing power by means of an electric acoumeter. *Laryngoscope* 23:960–964.
- Guttman J, Ham LB. (1930) Masking effects of an interfering tone upon a deafened ear. *Laryngoscope* 40:648–654.
- Hartley RVL. (1928) "TU" becomes 'Decibel'. *Bell Lab Rec* 7(4):137–139.
- Hartmann A. (1887) *The Diseases of the Ear and Their Treatment*. Erskine J, trans. New York: G. P. Putnam's Sons. http://books.google.com/books?hl=en&lr=&id=G-zw4WIT6c0C&oi=fnd&pg=PA5&dq=diseases+of+the+ear+and+their+treatment&ots=k6vly_iGpa&sig=xHbGt1s1LGz63OKd65LBH5bYvZk#.
- Hughes DE. (1879) On an induction-currents balance, and experimental researches made therewith. *Proc R Soc Med* 29:56–65. <http://rspl.royalsocietypublishing.org/content/29/196-199/56.full.pdf>.
- Hughson W, Thompson E. (1942) Correlation of hearing acuity for speech with discrete frequency audiograms. *Arch Otolaryngol* 36:526–540. <http://archotol.jamanetwork.com/article.aspx?articleid=571880>.
- Jerger J. (2013) Why the audiogram is upside-down. *Int J Audiol* 52(3):146–150.

- Katz J. (1972) *Handbook of Clinical Audiology*. Baltimore: Williams and Wilkins.
- Kennelly AE. (1935) Adoption of the Meter-Kilogram-Mass-Second (M.K.S.) Absolute System of Practical Units by the International Electrotechnical Commission (I.E.C.), Bruxelles, June, 1935. *Proc Natl Acad Sci USA* 21(10):579–583. www.pnas.org/content/21/10/579.full.pdf+html.
- Martin MH. (1929) Decibel—the name for the transmission unit. *Bell Syst Tech J* 8:1–2. www.alcatel-lucent.com/bstj/vol08-1929/articles/bstj8-1-1.pdf.
- Minton JP, Wilson JG. (1921) The sensitivity of normal and defective ears for tones at various frequencies. *Proc Inst Med Chic* 3: 157–171.
- Newby HA. (1958) *Audiology Principles and Practice*. New York: Appleton-Century-Crofts.
- Pirilä T, Jounio-Ervasti K, Sorri M. (1992) Left-right asymmetries in hearing threshold levels in three age groups of a random population. *Audiology* 31(3):150–161.
- Pohlman AG. (1931) The possibilities in the quantitative correlation between air and bone-transmitted speech. *Laryngoscope* 41: 157–165.
- Richardson BW. (1879) Some researches with Professor Hughes' new instrument for the measurement of hearing; the audiometer. *Proc R Soc Med* 29:65–70. <http://rspl.royalsocietypublishing.org/content/29/196-199/65.full.pdf>.
- Ruppert L. (1956) *Brief History of the International Electrotechnical Commission*. Geneva: International Electrotechnical Commission. www.iec.ch/about/history/documents/pdf/IEC%20History%201906-1956.pdf.
- Schlauch RS, Nelson P. (2009) Puretone evaluation. In: Katz J, Medwetsky L, Burkard R, Hood L, eds. *Handbook of Clinical Audiology*. 6th ed. Baltimore: Lippincott Williams and Wilkins, 30–49.
- Sivian LJ, White SD. (1933) On minimum audible sound fields. *J Acoust Soc Am* 4:288–321.
- Steinberg JC, Montgomery HC, Gardner MB. (1940) Results of the World's Fair hearing tests. *J Acoust Soc Am* 12:291–301.
- Stevens SS, Davis H. (1938) *Hearing: Its Psychology and Physiology*. New York: Wiley.
- Système International d'Unités. (1960) 11th Conférence Générale des Poids et Mesures (CGPM). Resolution 12. www.bipm.org/en/CGPM/db/11/12/.
- Thompson EA. (1947) Methods for recording audiometric findings recommended by the Committee on the Conservation of Hearing. *Trans Am Acad Ophthalmol Otolaryngol* 51:362–370.
- Wegel RL. (1922) The physical examination of hearing and binaural aids for the deaf. *Proc Natl Acad Sci USA* 8(7):155–160. www.ncbi.nlm.nih.gov/pmc/articles/PMC1085080/pdf/pnas01892-0003.pdf.
- Wilson RH. (2011) Some observations on the nature of the audiometric 4000 Hz notch: data from 3430 veterans. *J Am Acad Audiol* 22(1):23–33.
- Wilson RH, McArdle R. (2013) Characteristics of the audiometric 4,000 Hz notch (744,553 veterans) and the 3,000, 4,000, and 6,000 Hz notches (539,932 veterans). *J Rehabil Res Dev* 50(1): 111–132.
- Yantis PA. (1985) Puretone air-conduction threshold testing. In: Katz J, ed. *Handbook of Clinical Audiology*. 3rd ed. Baltimore: Williams and Wilkins, 153–169.
- Yantis PA. (1994) Puretone air-conduction threshold testing. In: Katz J, ed. *Handbook of Clinical Audiology*. 4th ed. Philadelphia: Lippincott Williams and Wilkins, 97–108.



Appendix A. Arithmetic and Logarithmic Mean Differences

As used in this paper, inter-octave frequency is the arithmetic mean frequency of the two bounding octave frequencies and is represented on the audiogram as either the “appropriate place on a logarithmic scale” (ASHA, 1990) or centered between the octave frequencies (ANSI, 2004), that is, the arithmetic midpoint. The latter convention is used in the current ANSI (2010) standard for audiometers to specify the interoctave frequencies. Because frequency on the audiogram is in log₁₀ units, the arithmetic midpoint representation of the interoctave frequency is misleading and can produce errors when making threshold calculations involving interoctave frequencies. The data in Table A1 demonstrate this point. In the table, the 1000 Hz threshold is fixed at 10 dB HL, whereas the 2000 Hz threshold varies from 15 dB to 80 dB HL. The midpoint between

these thresholds at the octave frequencies varies depending on the metric used to make the calculation. The arithmetic mean of the two thresholds, which would be at 1500 Hz, is the simple average of the 1000 and 2000 Hz thresholds and varies in the table from 12.5 to 45.0 dB HL. The logarithmic mean of the two thresholds, which is the half-octave frequency (1414 Hz), involves two steps. First, the two octave thresholds are converted to log₁₀ units and the average of the logs for the two thresholds computed. Second, the antilog of the average log₁₀ threshold is obtained to convert back to dB HL. This exercise demonstrates that as the arithmetic threshold difference for the octave frequencies increases from 12.5 to 45.0 dB, the logarithmic threshold difference is less, increasing from 12.2 to 28.3 dB. Thus, over the 5 to 70 dB differences between octave thresholds, the differences between the inter-octave thresholds (arithmetic) and the half-octave thresholds (logarithmic) ranged from 0.3 to 16.7 dB.

Table A1. Interoctave Frequency Thresholds Calculated Arithmetically (1500 Hz) and Logarithmically (1414 Hz) for Various 1000 and 2000 Hz Threshold Differences Listed along with the Differences Obtained with the Two Methods

1000 Hz threshold		2000 Hz threshold		Interoctave frequency		Difference (dB)
				1500 Hz	1414 Hz	
(dB HL)	log ₁₀	(dB HL)	log ₁₀	Arithmetic (dB HL)	Logarithmic (dB HL)	
10	1	15	1.176091	12.5	12.2	0.3
10	1	40	1.602060	25.0	20.0	5.0
10	1	45	1.653213	27.5	21.2	6.3
10	1	50	1.698970	30.0	22.4	7.6
10	1	55	1.740363	32.5	23.5	9.0
10	1	60	1.778151	35.0	24.5	10.5
10	1	65	1.812913	37.5	25.5	12.0
10	1	70	1.845098	40.0	26.5	13.5
10	1	75	1.875061	42.5	27.4	15.1
10	1	80	1.903090	45.0	28.3	16.7